



A Modeling Framework for Optimizing F-35A Strategic Basing Decisions to Meet Training Requirements

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Preface

Domestic basing decisions can have significant implications for the U.S. Air Force (USAF) in terms of the costs and risks associated with meeting mission requirements. Strategic basing is an important and timely topic given the large number of pending basing decisions for the F-35A, which will soon enter full-rate production and eventually constitute a significant portion of the future USAF fighter force structure.

This work extends recent RAND Project AIR FORCE (PAF) analyses that have addressed different aspects of the Air Force Strategic Basing Process:

- *Shaping Domestic Basing Decisions to Ensure Affordable Readiness: A Screening-Level Assessment of Alternative Domestic Basing Postures for the F-35A*, Sean Bednarz, Anu Narayanan, Paul DeLuca, Joshua Baron, Robert A. Guffey, Daniel M. Romano, and Joseph V. Vesely, 2015, not available to the general public.
- *Improvements to Air Force Strategic Basing Decisions*, Constantine Samaras, Rachel Costello, Paul DeLuca, Stephen J. Guerra, Kenneth Kuhn, Anu Narayanan, Michael Nixon, Stacie L. Pettyjohn, Nolan Sweeney, Joseph V. Vesely, Lane F. Burgette, 2016.

PAF work in fiscal year (FY) 2013 showed that the basing process uses authoritative and consistent data to make individual basing decisions but does not systematically and quantitatively make enterprisewide assessments that incorporate broader USAF strategic concerns into each basing decision (Samaras et al., 2016). To begin to address this gap, PAF developed a methodology in FY 2014 to assess the cost, effectiveness, and risk associated with different basing postures representing different degrees of fleet consolidation and geographic distribution. Using the F-35A as an exemplar, the FY 2014 project showed that moderate consolidation of the F-35A fleet around potential fifth-generation training ranges could save substantial one-time and recurring costs, while enabling more aircraft to be based near advanced training ranges capable of supporting fifth-generation fighter training (Bednarz et al., 2015). It suggested focusing limited range modernization dollars on a few ideally suited training ranges and heavily weighting proximity to these ranges in the basing process for future F-35A operational units.

Two developments strengthen the case for considering anticipated locations of suitable training ranges and accounting for existing and emerging training requirements for the F-35A in making future basing decisions. First, USAF is in the midst of making plans to upgrade a subset of the service's training ranges to enable fifth-generation aircraft, such as the F-35A, to train in environments similar to those that may be encountered in conflicts with near-peer adversaries (Air Combat Command [ACC], 2014). Second, the latest F-35A Ready Aircrew Program Tasking Memorandum requires completion of four composite force-training (CFT) events

annually for all combat mission-ready (CMR) pilots, in addition to participation in two flag exercises for inexperienced pilots and one flag exercise for experienced pilots (ACC, 2015a). While these requirements are consistent with those for some fourth-generation fighters, the advanced capability of the F-35A and the large number of F-35A pilots expected to be proficient at suppression of enemy air defenses against advanced threats in contested environments increase the importance of proximity to advanced training ranges where regular CFT events can support these requirements within flying hour constraints.

The modeling framework presented in this report is designed to identify basing locations for the F-35A fleet and training range locations that minimize enterprisewide flying costs associated with participation in required CFT training exercises for CMR pilots. This modeling framework was developed as part of the FY 2015 “Shaping Domestic Basing Postures to Ensure Strategic Agility” project, commissioned by the Principal Deputy Assistant Secretary of the Air Force for Installations, Environment, and Energy and conducted within the PAF Resource Management Program.

RAND Project AIR FORCE

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Summary

Domestic basing decisions can have significant implications for the U.S. Air Force (USAF) in terms of the costs and risks associated with meeting mission requirements. Given the large number of pending basing decisions for the F-35A, which will soon enter full-rate production and eventually constitute a significant portion of the future USAF fighter force structure, strategic basing is an important and timely topic. This report describes the framework for an optimization model that minimizes the enterprise operations and support costs associated with composite force–training (CFT) events required for F-35A continuation training. Specifically, the modeling framework is designed to identify a basing strategy that minimizes enterprisewide flying costs associated with participation in required CFT events for all F-35A combat mission–ready pilots.¹ One key assumption in this work is that some of these events will be LFE exercises that must take place at advanced training ranges modernized to “replicate real world combat environments across the full range of military operations” (Air Combat Command [ACC], 2014) and that the number of such ranges will be limited due to land, airspace, and fiscal constraints. The modeling framework detailed here selects F-35A basing locations and training event locations from sets of likely candidates so that cost is minimized and CFT requirements are satisfied. By identifying training event locations that yield the lowest-cost basing solution, the framework also provides insight into potentially cost-effective candidates for range modernization. The two key model outputs—the optimal basing strategy and event locations—are interdependent and optimized together.

The modeling framework accepts inputs in the following categories:

- candidate F-35A basing locations
- F-35A attributes—e.g., fuel consumption characteristics and cost per flying hour
- pilot continuation training requirements—specifically Ready Aircrew Program requirements for CFTs
- attributes of training exercises—e.g., what portion of CFTs must take place at advanced ranges and how many aircraft can participate in such exercises
- candidate CFT locations
- locations of supporting mission design series aircraft wings and other attributes.

The outputs of the model include base assignments of the wings, the location of each training event, the number of aircraft each wing sends to each training event from its assigned base, and

¹ *CFT events* are defined in the Air Force Instruction for F-35 Aircrew Training as, “Scenarios employing multiple flights of aircraft, each under the direction of its own flight leader, acting in a large force–employment (LFE) scenario to achieve a common tactical objective. Scenarios should be opposed by air and surface threats and should include at least 8 blue aircraft.” (ACC, 2010)

the total flying hour costs associated with travel to training events. Only the costs associated with participating in regional training exercises were included in this assessment. Other costs, such as flying at local primary training ranges, and other constraints, such as airspace restrictions, would also be important considerations in future basing decisions.²

Ultimately, basing decisions are up to USAF to make as part of the strategic basing process. The modeling framework described in this report can help USAF make these decisions. In addition to providing specific insights regarding the costs associated with a portion of F-35A training requirements, this framework is intended to help USAF policymakers identify and address key policy issues pertaining to the value and cost of strategic basing initiatives. This report presents potential applications for the presented modeling framework and provides guidance on how it might be used to understand the implications of strategic basing. For instance, this framework can be used to understand and articulate the value of strategic basing, and assess tradeoffs between recurring and one-time costs associated with basing decisions. Decisionmakers can use the presented framework to help answer such questions as:

- What is the difference in CFT costs between the planned basing strategy and the optimal basing strategy?
- What is the trade-off between flying hour costs and costs of range modernization?
- What is the contribution of other platforms that support F-35 training to total flying hour costs?

² Key model assumptions and limitations are described in Chapter One.

Acknowledgments

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Maj Gen H. D. Pumbo Jr., Commander, Ninth Air Force, Air Combat Command (ACC), and his staff graciously hosted our team as observers of the July Razor Talon exercise at Seymour Johnson Air Force Base. We are thankful for the time Gen Pumbo dedicated to discussing the genesis, current status, and future of this important monthly training event and the East Coast Battlespace. Many individuals contributed support, providing visibility into the planning leading up to the exercise, sharing insight and answering questions during our visit, and participating in follow-up discussions after our departure. While there are too many to name here, we would like to recognize Lt Col Ernesto "Pong" DiVittorio, Maj William Seefeldt, Maj Dusten "Postal" Weathers, Capt Charles "Nordo" Price, and Lt Col Jason "Trap" Watson.

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³ All offices and ranks are current as of the time of this research.

Abbreviations

| | |
|------|--------------------------------|
| ACC | Air Combat Command |
| AFI | Air Force Instruction |
| CFT | composite force–training |
| CMR | combat mission–ready |
| FY | fiscal year |
| LFE | large force–employment |
| MDS | mission design series |
| PAA | primary aircraft authorization |
| PAF | Project AIR FORCE |
| PTR | primary training range |
| RAP | Ready Aircrew Program |
| TDY | temporary duty |
| USAF | U.S. Air Force |

1. Introduction

The Importance of Training Requirements for F-35A Basing Decisions

Strategic basing is a key issue for the U.S. Air Force (USAF). Domestic basing decisions can have serious implications for costs and risks associated with meeting mission requirements. Adding importance to the topic is the addition of fifth-generation aircraft: These aircraft involve a significant number of pending basing decisions, are relatively expensive to fly, and require advanced live training that the existing USAF training range enterprise cannot provide for certain skills and missions.

RAND Project AIR FORCE (PAF) work in fiscal year (FY) 2014 suggested focusing limited range modernization dollars on a few ideally suited training ranges and heavily weighting proximity to these ranges in the basing process for future F-35A operational units. Two developments strengthen the case for considering anticipated locations of suitable training ranges and accounting for existing and emerging training requirements for the F-35A in making future basing decisions. First, USAF is in the midst of making plans to upgrade a subset of its training ranges to enable fifth-generation aircraft, such as the F-35A, to train in environments similar to those that may be encountered in conflicts with near-peer adversaries (Air Combat Command [ACC], 2014). Sensors on fifth-generation aircraft require access to high-fidelity targets, access to higher-density threats, and live training against advanced threats. The current USAF range enterprise is not positioned to provide training of this nature, and some fraction of ranges will need to be modernized to include the necessary upgrades based on the frequency and complexity of training they are anticipated to support. One implication of selectively upgraded training ranges and the advanced training needs of fourth- and fifth-generation aircraft is that a “graduated” training strategy would emerge—one that includes frequent exercises conducted locally and less-frequent and more-complicated exercises conducted regionally or nationally at advanced training ranges. The locations and frequency of these regional training exercises, combined with where fifth-generation aircraft are based, would have implications for enterprisewide costs.⁴

Second, the latest F-35A Ready Aircrew Program (RAP) Tasking Memorandum requires completion of four composite force–training (CFT) events annually for all combat mission–ready (CMR) pilots, in addition to participation in two flag exercises for inexperienced pilots and one flag exercise for experienced pilots (ACC, 2015a).⁵ For F-35A training, CFT events are defined as “scenarios employing multiple flights of aircraft, each under the direction of its own flight

⁴ Discussions with AF/A3, 2015.

⁵ ACC (2010) defines *flag exercise events* as “missions flown in formal MAJCOM-sponsored exercises (i.e. Red Flag, Green Flag, etc.)” that “...will include operations with Full Scale Inert/Live ordnance.”

leader, acting in a large force–employment (LFE) scenario to achieve a common tactical objective. Scenarios should be opposed by air and surface threats and should include at least 8 blue aircraft” (ACC, 2010). CFT events could, in theory, involve similar aircraft from the same or proximate units flying together in different roles. But at least some CFT events will likely involve multiple types of aircraft training together at modernized ranges to provide pilots experience flying with other aircraft in realistic scenarios against advanced threats.

Currently, fighters accomplish the RAP through live flight training in local “backyard” primary training ranges (PTRs), simulator training, and occasional participation in flag exercises. However, the USAF believes that programmed advances in platform and sensor capability and standoff weapon ranges will soon exceed the capability of our range enterprise.⁶ This introduces a challenge for providing realistic CFT events needed to support F-35A RAP requirements and mission commander upgrades. These developments increase the importance of proximity to advanced ranges selected for modernization; regular transits to these locations from distant bases would strain unit flying hour programs.

It is uncertain how the size, complexity, location, and other details of CFT and flag exercises will evolve to support fifth-generation fighter training.⁷ Nevertheless, now is the time to lay the groundwork for reductions in future flying costs by making strategic basing decisions that consider proximity to potential training locations for such events. The framework introduced in this report enables analysis that can lead to such reductions.

Modeling Framework Overview

RAND PAF developed a model designed to identify a basing posture that minimizes enterprisewide flying costs associated with participation in required CFT training exercises for CMR pilots. Outputs of the model include the training event locations that yield the lowest-cost basing solution, providing insight into potentially cost-effective candidates for range modernization.⁸ The optimization algorithm calculates total costs—including flying hour costs incurred by the F-35A and supporting aircraft during their transits to training events—and uses flying hour costs as the sole performance metric for identifying the optimal F-35A beddown strategy and cost-minimizing training locations. It does not consider temporary duty (TDY) or

⁶ Discussions with AF/A3, 2015.

⁷ The presented framework does not differentiate CFT events by their size, complexity, location, or other attributes. If requirements evolve in such a way that not all CFT events can be treated the same, the presented framework would need to be expanded to accommodate this differentiation among CFT events.

⁸ This work does not aim to provide a full cost-benefit assessment of candidates for range modernization because that would require added analysis of the actual costs associated with completing upgrades, which are unknown and likely to vary by site. As costs associated with range upgrades become known or less uncertain, they can be implemented in the framework by adding a parameter that considers upgrade costs in determining the optimal solution.

any other costs associated with aircrews attending training exercises, since these represent a small fraction of the overall costs and would not vary much between postures.⁹

Inputs to the model include training requirements for CMR pilots pertaining to attendance at CFT events and flag exercises (differentiated by experience level), candidate installations for bedding down F-35As, and candidate training event locations. Given that the focus of this work is on F-35A basing, legacy fighter (F-16 and A-10) bases are used as candidate locations for the F-35A fleet. While the Air Force Strategic Basing Process employs an enterprisewide list of bases for each basing decision, the ACC “F-35A Fleet Basing Strategy” (2015b) provides several reasons to believe that legacy fighter bases will be prime candidates for the F-35. The following points support this assumption:

- Previous plans replaced F-16s and A-10s on a one-for-one basis. (ACC, 2015b, p. 6)
- Since the F-35A will replace legacy fighters, is comparable in size to the F-16 and A-10, and will be fielded in squadron sizes that mainly match current fighter units, basing F-35As at locations currently hosting fighters and in equivalent numbers will save significant costs in facility construction. In addition, current fighter bases have access to ranges and airspace that are more likely to be able to accommodate F-35A training than other locations. (ACC, 2015b, p. 9)
- The F-35A is an F-16/A-10 replacement, so for the purposes of scoring a particular installation, any facilities or resources in use to support the F-16/A-10 will be considered available for a future F-35A mission. Capitalizing on available existing facilities for alteration versus new construction can appreciably reduce beddown costs. (ACC, 2015b, p. 11)

The optimization algorithm constrains attributes of candidate F-35A beddown locations including base type (active component, Air Force Reserve Command, or Air National Guard) and squadron size and count at basing locations. We assume that aircraft supporting F-35A training at CFT events remain based at their current locations. Candidate training exercise locations and attributes of training events—including event size and frequency for a given range—and the number of total ranges included in the optimization space are inputs to the model.

The framework is intended to provide insight to USAF on the following key questions:

- What are the marginal flying hour costs associated with participation at regional training exercises for the F-35A and supporting mission design series (MDS)?
- Where should the F-35A fleet be based to minimize flying hour costs associated with meeting requirements for attendance at regional training exercises?

⁹ Razor Talon, a monthly LFE held at Seymour Johnson Air Force Base, is the model used for training events in this analysis. For that event, the only TDY costs are typically those incurred by fighter pilots who arrive a day before the exercise to participate in mission planning and briefing. Bombers, Battle Management Command and Control platforms, and tankers typically depart and return to home base on the day of the exercise. Maintainers do not deploy.

- Where and how often should regional training events be held in order to minimize flying costs?

Assumptions and Limitations

We make a few key assumptions in the model formulation that have notable implications for results. Assumptions are separate from inputs, which can be adjusted and are described in Chapter Two. The following assumptions are implicit to the framework and should be taken into consideration when analyzing outputs of the optimization:

- Flying hour costs are the only costs calculated and serve as the primary performance metric for selecting the optimal solution. Flying hour costs are a function of the cost per flying hour for each included MDS and the total flying hours associated with all aircraft flying to and from a chosen set of range locations to participate in required training exercises.¹⁰ The model does not capture TDY or other costs associated with exercise participation, or the costs associated with upgrading individual training locations to meet advanced training needs.
- All aircraft basing is held static with the exception of the F-35A fleet. While the flying hour costs associated with attendance at training exercises are calculated for all included aircraft, their home locations are fixed.
- Only a portion of the F-35A flying program requirements is considered in the optimization—namely, participation in regional training exercises. Furthermore, all training exercises are seen as interchangeable, with no important differences in other platform participation requirements or training benefits.¹¹
- The model formulation assumes that aircraft are always available as scheduled for exercise participation—i.e., it does not account for possible failures during transit to or upon arrival at training locations. One possible effect of this assumption is that results might slightly underestimate flying hour costs by undercounting the total number of flying hours needed to meet requirements.
- Aircraft are sent to events as two-ships; thus, single pilots are never sent to events, even if this causes some pilots to exceed training requirements.
- Costs and other constraints (such as airspace restrictions) associated with training at local PTRs to fulfill RAP training requirements are important considerations not included in

¹⁰ Cost per flying hour for each MDS was estimated using Air Force Instruction (AFI) 65-503 (USAF, 2012). In calculating the total flying hours, fighters transiting distances greater than their maximum range are assessed a flying hour penalty for refueling the aircraft and to account for potential route inefficiencies.

¹¹ We focused on costs associated with participation in CFT events because we believe this portion of training requirements represents additional flying hours beyond those associated with RAPs for current fighters. In a budget-constrained environment, it might not be possible to find funding for these additional hours, in which case proficiency might be threatened.

this work for two reasons: (1) The Air Force Strategic Basing Process already considers these aspects in a sophisticated way; and (2) issues related to training at local PTRs are likely to become less important for the F-35A as training missions are moved from PTRs to simulators and to CFTs conducted at more-advanced ranges.

Organization of This Report

This report details only the model framework and formulation and does not present results of analysis completed using the framework.

Chapter Two presents a technical overview of the modeling framework, including details about inputs and outputs. Chapter Three presents the mathematical formulation underlying the model and is intended for modelers and analysts who are familiar with optimization techniques. Chapter Four provides an overview of potential applications.

2. Modeling Framework Description

This chapter describes technical characteristics of the model. An optimization approach allows for quick and efficient exploration of the relatively large problem space. The underlying method is a mixed integer programming algorithm developed using the General Algebraic Modeling System. In addition to calculating the flying hour costs associated with participation at regional training events for the F-35A and supporting platforms, the optimization model selects the F-35A basing strategy that yields the lowest flying hour costs.

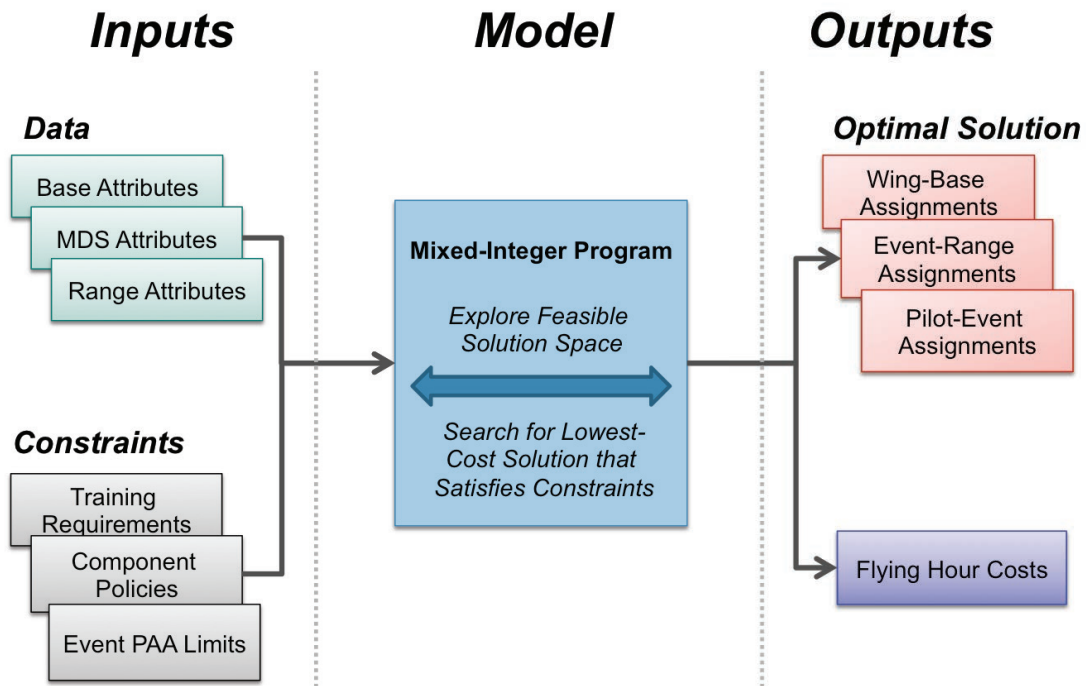
The optimal solution includes a least-cost assignment of F-35A wings to candidate bases, training events to candidate ranges, and pilots to training exercises in such a way that requirements for participation at regional training events are met. The outcome of each of these three decisions is dependent on the other two decisions.¹² For example, ideal basing locations are near ranges that host training exercises because costs are made up entirely of the expenses associated with aircraft traveling between bases and training locations. Similarly, reasonable assignment of two-ships to training exercise locations requires knowing where these exercises are held, but also where participating wings are based.

The model constrains both total required participation in training events and the number of training events a range may host annually, and it ensures that base component policies are met in bedding down wings (e.g., active-duty wings are assigned to active-duty bases). Figure 2.1 provides an overview of model structure.

The modeling framework allows adjustments to parameter values to explore different scenarios of interest. For instance, input data (such as the set of candidate F-35A bases or candidate ranges for training exercises) or constraint parameters (such as limits on the size of training events or the number of events a range can host annually) can be varied to identify optimal beddowns for different conditions.

¹² To simplify the problem space and conserve computational resources, we formulate it as a network problem, which solves very quickly (with each model run taking only up to a few minutes).

Figure 2.1. Modeling Framework Overview



NOTE: PAA=primary aircraft authorization.

The remainder of this chapter describes model inputs and associated parameters and provides details of how the optimization algorithm calculates outputs.

Inputs

The model accepts inputs in the following categories:

- candidate F-35A basing locations
- F-35A attributes—e.g., fuel consumption characteristics and cost per flying hour
- pilot continuation training requirements—specifically RAP requirements for CFTs
- attributes of training exercises—e.g., what portion of CFTs must take place at advanced ranges and how many aircraft can participate in such exercises
- candidate CFT locations
- locations of supporting MDS aircraft wings and other attributes.

Inputs are either specifications of the optimization space (e.g., the list of candidate bases from which to select locations for bedding down the F-35A fleet) or constraints that limit whether and how a particular element of the optimization space can be used (e.g., a parameter limits assignment of an active F-35A wing to an active-duty base, and another limits the number

of training exercises that can be hosted by a given training range). The values that inputs take can be changed to mimic scenarios of interest.

Candidate Basing Locations and Wing and Squadron Considerations

The pool of candidate locations from which a beddown solution is chosen can be any set of bases. Since this work is focused on informing F-35A basing decisions and is rooted in understanding the cost implications of training requirements for the F-35A, a reasonable candidate set for instantiation of the optimization would include those bases that are likely to receive F-35A wings (e.g., bases with legacy aircraft, such as F-16s and A-10s).

The framework allows wings of the different service components to be treated differently to account for real-world considerations associated with matching wing and base type (AC, AFRC, ANG). For example, one set of parameters ensures that active-duty wings are only assigned to active-duty bases. A different parameter limits the number of wings of a component type at a single base—for instance, this parameter can be used to impose the restriction that no more than one wing of any component can reside at a single base, or that individual wings from each of the components can reside at a single base. Another set of parameters allows for variability in squadron size and number of squadrons per wing as a function of component type to reflect reality. The algorithm weights proximity to exercise locations differently for different wing types when assigning wings to bases. Since the largest wings potentially represent the largest transportation costs in attending events, those wings are generally assigned to eligible bases nearest a training range. This helps to minimize the total cost of transporting F-35A aircraft to training exercise locations.

Training Requirements

The only training requirements considered in this work are those associated with participation at regional training events for F-35A CMR pilots. Key inputs that characterize this training requirement include a parameter that sets the number of training exercises that each pilot must attend annually, and another that sets the number of pilots per aircraft that may train at a single event.

Locations and Attributes of Training Exercises

The number of usable ranges may be set using two parameters that control the minimum and maximum number of ranges that may be used. Together, these parameters provide a way to explore the ramifications of range modernization decisions for basing decisions and training event requirements. For example, if only a few ranges are modernized and capable of hosting F-35A training events, the model can be used to understand the impacts of holding training events only at these locations, which will aid in making basing decisions, both in terms of costs and level of consolidation.

The framework includes a parameter that limits the maximum number of aircraft that may participate in a single training event, common across training locations. This constraint reflects

the idea that very large events are likely to diminish the utility of the exercise, or that ranges are capacity constrained. Another parameter limits the maximum number of training events that may occur at a single range due to workload considerations.

This limit on event participation affects the number of events that must take place in order to accommodate all pilot training. Reducing the maximum number of participants that may attend each event means more training events would be needed to meet requirements for participation in regional training exercises and vice versa. The limit on training events per range affects the number of ranges that must be used for events. Again, when the limit on the number of events per range is low, more ranges must be used to host the required events. If both the participation and event count limits are set too low, the number of available training opportunities may be insufficient to fulfill training requirements.

Locations and Attributes of Supporting MDS

Unlike F-35A wings, the locations of the supporting platforms are assumed to be fixed and treated as inputs.¹³

Optimizing for Cost

Costs are calculated as the sum total of all flying hour costs incurred by the F-35A fleet, as well as by other aircraft that travel to exercise locations to support training. F-35As fly from a base chosen by the optimization algorithm to the training event host range, whereas other participating aircraft are assumed to fly to events from their home locations. As can be expected, the primary driver of costs, as well as beddown and training range location decisions, is the sum of distances between bases and ranges. When only the F-35A aircraft are taken into account, cost-effective basing and event assignment decisions tend to host events at the ranges that have one or more bases nearby, and to assign F-35A wings to those bases.

The costs incurred by F-35A aircraft at a specific event vary—each additional participating aircraft adds to the total costs of the event, whereas the costs incurred by the other platforms are fixed costs per event. The optimization algorithm takes into account this significant fixed cost when considering whether to add an additional training event rather than sending aircraft to existing events with remaining capacity.

Outputs

The outputs of the model include the assignment of wings to bases, the optimal locations of training events, the number of aircraft each wing sends to each training event from its assigned base, and the total flying hour costs associated with travel to training events for all participating aircraft.

The next chapter presents the detailed mathematical formulation underlying the model.

¹³ It is out of the scope of this analysis to consider the possibility of already-based platforms being moved from their home locations.

3. Mathematical Formulation

As described in Chapter Two, the optimization algorithm seeks to assign F-35A wings to bases, training events to ranges, and F-35A two-ships (F-35A pairs) to training events such that F-35A pilot training event attendance requirements are fulfilled at minimum cost. Note that this formulation offers no guidance on choosing which specific aircraft or pilots should participate in each event; that assignment could be accomplished easily with a heuristic or secondary optimization.

In this chapter, we list and define key elements of the model formulation and, as applicable, describe the types of calculations performed. This section is meant for analysts and modelers who may choose to build on parts of this formulation or use it in its complete form.

Sets

| | |
|-----|---|
| W | set of F-35A wings, including Air National Guard and Reserve wings, and active-duty wings with two or three squadrons |
| E | set of training events |
| B | set of bases, including active-duty, Air National Guard, and Reserve bases |
| R | set of training ranges |
| S | set of states (in the United States) |

Constants

The optimization uses the following constants:

| | |
|-------------------|---|
| $CPFH_F35$ | cost per flying hour of the F-35A |
| $CPFH_BMC2$ | cost per flying hour of the BMC2 aircraft |
| $CPFH_BOMBER$ | cost per flying hour of the bomber |
| $CPFH_F22$ | cost per flying hour of the F-22 |
| $TRANSIT_SPEED$ | speed all aircraft fly when transiting between home bases and event ranges |
| $PILOTS_PER_AC$ | number of CMR pilots that may attend a training event for each aircraft attending |
| CMR_ANG | number of CMR pilot-pairs in a National Guard wing |
| CMR_AFR | number of CMR pilot-pairs in a Reserve wing |
| CMR_AD2 | number of CMR pilot-pairs in an active-duty wing with two squadrons |
| CMR_AD3 | number of CMR pilot-pairs in an active-duty wing with three squadrons |
| PAA_ANG | number of two-ships in a National Guard wing |
| PAA_AFR | number of two-ships in a Reserve wing |
| PAA_AD2 | number of two-ships in an active-duty wing with two squadrons |

| | |
|-----------------------|---|
| PAA_AD3 | number of two-ships in an active-duty wing with three squadrons |
| MIN_EVENTS | minimum number of events that each F-35A pilot must attend |
| MIN_RANGES | minimum number of ranges that must host events |
| MAX_RANGES | maximum number of ranges that can host events |
| $MAX_ATTENDEES$ | maximum number of two-ships that can attend a single event |
| MAX_RANGE_EVENTS | maximum number of events a training range can host in a year |
| $DISTANCE[b,r]$ | great-circle distance in nautical miles between base b and range r |
| $DISTANCE_BMC2[r]$ | great-circle distance in nautical miles that BMC2 aircraft must travel from home bases to range r |
| $DISTANCE_BOMBER[r]$ | great-circle distance in nautical miles that bomber aircraft must travel from home bases to range r |
| $DISTANCE_F22[r]$ | minimum great-circle distance in nautical miles that F-22 aircraft must travel from home bases to range r |
| $WING_ANG[w]$ | equal to 1 if wing w is an Air National Guard wing, and 0 otherwise |
| $WING_AFR[w]$ | equal to 1 if wing w is an Air Force Reserve wing, and 0 otherwise |
| $WING_AD[w]$ | equal to 1 if wing w is an active-duty wing, and 0 otherwise |
| $WING_AD2[w]$ | equal to 1 if wing w is an active-duty wing with two squadrons, and 0 otherwise |
| $WING_AD3[w]$ | equal to 1 if wing w is an active-duty wing with three squadrons, and 0 otherwise |
| $BASE_STATE[b,s]$ | equal to 1 if base b is located in state s , and 0 otherwise |
| $BASE_AD[b]$ | equal to 1 if base b is an active-duty base, and 0 otherwise |

Integer Variables

The following variable assigns two-ships from bases to events, and events to ranges:

| | |
|------------|--|
| $P[b,r,e]$ | number (integer) of two-ships that fly from base b to range r during event e |
|------------|--|

Binary Variables

The following variable assigns F-35A wings to bases:

| | |
|----------|--|
| $G[w,b]$ | equal to 1 if wing w is assigned to base b , and 0 otherwise |
|----------|--|

The following variables are indicator variables used to enforce constraints:

| | |
|-----------|--|
| $y1[e,r]$ | equal to 1 if event e is held at range r , and 0 otherwise |
| $y2[r]$ | equal to 1 if any event is held at range r , and 0 otherwise |

Calculated Values

The optimization relies on the following calculated values:

$Cost_TwoShip[b, r, e]$ cost of sending two-ships from base b to range r during event e :

$$Cost_TwoShip[b, r, e] = P[b, r, e] * Cost_F35[b, r]$$

$Cost_F35[b, r]$ cost for a two-ship to travel from base b to range r :

$$Cost_F35[r] = CPFH_F35 * 2 * DISTANCE[b, r] / TRANSIT_SPEED$$

$Cost_BMC2[r]$ cost for two E-3s to travel from their bases to range r :

$$Cost_BMC2[r] = CPFH_BMC2 * 2 * DISTANCE_BMC2[r] / TRANSIT_SPEED$$

$Cost_BOMBER[r]$ cost for two bombers to travel from their bases to range r :

$$Cost_BOMBER[r] = CPFH_BOMBER * 2 * DISTANCE_BOMBER[r] / TRANSIT_SPEED$$

$Cost_F22[r]$ cost for four F-22s to travel from the closer of their bases to range r :

$$Cost_F22[r] = CPFH_F22 * 4 * DISTANCE_F22[r] / TRANSIT_SPEED$$

$BIGM$ maximum number of attendees at a single range across events:

$$BIGM = CARDINALITY[E] * MAX_ATTENDEES$$

Objective Function

The objective is to minimize z , the total cost of transporting all aircraft from their assigned bases to training events, under all possible event-range, wing-base, and two-ship-event assignments.

$$\begin{aligned} \min z \\ &= \sum_B \sum_R \sum_E Cost_TwoShip[b, r, e] \\ &+ \sum_E \sum_R y_1[e, r] * (Cost_BMC2[r] + Cost_BOMBER[r] + Cost_F22[r]) \end{aligned}$$

Constraints

The first constraint, C1, ensures that each wing is assigned to a base and not to multiple bases. For each wing w , values of $G[w, b]$ must equal 0 for all bases b , except the base to which wing w is assigned.:

$$C1: \quad 1 = \sum_B G[w, b] \quad \text{for each } w \in W$$

Constraint C2 requires that all CMR pilots (as part of two-ships) attend the appropriate number of training events. To do this, we set a lower bound on the total number of CMR pilot-pairs that must be sent to training events from each base b . At the core of this lower bound is the calculation of the number of CMR pilot-pairs that require training for a given wing, using the following sum, whose terms consist entirely of data:

$$CMR_ANG * WING_ANG[w] + CMR_AFR * WING_AFR[w] + CMR_AMD2 * WING_AD2[w] + CMR_AD3 * WING_AD3[w]$$

Each term of this sum will be 0, except for the term corresponding to the component of wing w , resulting in the total pilot pairs in the wing. Next, we calculate the number of pilot-pairs that wing w contributes to the total number of CMR pilot-pairs at base b . To do so, we incorporate the decision variable $G[w,b]$, which equals 0 unless wing w is actually assigned to base b , into the previous sum:

$$CMR_ANG * WING_ANG[w] * G[w,b] + CMR_AFR * WING_AFR[w] * G[w,b] + CMR_AD2 * WING_AD2[w] * G[w,b] + CMR_AD3 * WING_AD3[w] * G[w,b]$$

Each term of this sum will be 0 except when the component type of wing w is correct, and when wing w is actually assigned to base b , resulting in the total number of CMR pilots in wing w assigned to base b . The total number of CMR pilot-pairs at base b is calculated by summing the previous equation over all wings w :

$$\sum_w \left(\begin{aligned} &(CMR_ANG * WING_ANG[w] * G[w,b]) + \\ &(CMR_AFR * WING_AFR[w] * G[w,b]) + \\ &(CMR_AD2 * WING_AD2[w] * G[w,b]) + \\ &(CMR_AD3 * WING_AD3[w] * G[w,b]) \end{aligned} \right)$$

CMR pilots in each wing are required to attend at least MIN_EVENTS . Therefore, the number of two-ships leaving each base b for a training event must equal the number of pilot-pairs in each wing assigned to that base, multiplied by the minimum number of events each pilot is required to attend, divided by the number of pilots that may share a single aircraft at an event for training purposes:

$$C2. \quad \sum_E \sum_R P[e,b,r] \geq MIN_EVENTS * \frac{\sum_w \left(\begin{aligned} &(CMR_ANG * WING_ANG[w] * G[w,b]) + \\ &(CMR_AFR * WING_AFR[w] * G[w,b]) + \\ &(CMR_AD2 * WING_AD2[w] * G[w,b]) + \\ &(CMR_AD3 * WING_AD3[w] * G[w,b]) \end{aligned} \right)}{PILOTS_PER_AC} \quad \text{for all } b \in B$$

While constraint C2 sets a lower bound on the total number of pilot-pair trips to training events that must originate from each base, constraint C3 requires that no more aircraft may leave any base b at one time (for a single event) than actually reside at that base. F-35A aircraft flying to event e from base b cannot exceed the number of aircraft that reside at base b . The formulation of constraint C3 is similar to that of C2:

$$\text{C3.} \quad \sum_R P[b, r, e] \leq \sum_W \left(\begin{aligned} &(PAA_ANG * WING_ANG[w] * G[w, b]) + \\ &(PAA_AFR * WING_AFR[w] * G[w, b]) + \\ &(PAA_AD2 * WING_AD2[w] * G[w, b]) + \\ &(PAA_AD3 * WING_AD3[w] * G[w, b]) \end{aligned} \right) \quad \text{for each } b \in B, \\ e \in E$$

Only one Air National Guard wing may reside at any individual base. Every term in the sum of constraint C4 is equal to 0 unless wing w is both a National Guard wing and assigned to base b . Constraint C4 ensures this can happen only once:

$$\text{C4.} \quad 1 \geq \sum_W (WING_ANG[w] * G[w, b]) \quad \text{for each } b \in B$$

Only one Air Force Reserve wing may reside at any individual base. The general form of constraint C5 is identical to that of the previous constraint:

$$\text{C5.} \quad 1 \geq \sum_W (WING_AFR[w] * G[w, b]) \quad \text{for each } b \in B$$

Only one active-duty wing may reside at any individual base. The general form of constraint C6 is identical to that of constraints C4 and C5:

$$\text{C6.} \quad 1 \geq \sum_W (WING_AD[w] * G[w, b]), \quad \text{for each } b \in B$$

Active-duty wings must reside at active-duty bases. In constraint C7, if base b is not an active-duty base, then the left-hand side of this inequality is equal to 0. If wing w is an active-duty wing, then the term $G[w, b]$ is forced to be 0 in order for the right-hand side of the equation to remain less than or equal to the left-hand side. And since $G[w, b]$ is forced to equal 0, the wing w cannot be assigned to base b . When the base b is active-duty, or when the wing w is not active-duty, the constraint is nonbinding.

$$\text{C7.} \quad BASE_AD[b] \geq WING_AD[w] * G[w, b] \quad \text{for each } w \in W, b \in B$$

Only one Air National Guard wing may reside in any individual state. Constraint C8 allows at most one wing w to simultaneously be a National Guard wing and assigned to a base b that is located in state s :

$$\text{C8.} \quad 1 \geq \sum_{W, B} (WING_ANG[w] * G[w, b] * BASE_STATE[b, s]) \quad \text{for each } s \in S$$

Constraint C9 ensures that indicator variable $y_1[e, r]$ must equal 1 when two-ships are assigned to event e at range r , since the variable $P[b, r, e]$ must equal 0 whenever $y_1[e, r]$ equals 0. Indicator variable $y_1[e, r]$ will be used in later constraints. C9 also ensures that no more than $MAX_ATTENDEES$ may attend a single training event:

$$\text{C9.} \quad MAX_ATTENDEES * y_1[e, r] \geq \sum_B P[b, r, e] \quad \text{for each } e \in E, r \in R$$

Each training event can be assigned to one and only one range. Constraint C10 forces y_l to be 0 for all ranges except one, for each unique event e :

$$\text{C10.} \quad 1 \geq \sum_R y_1[e, r] \quad \text{for each } e \in E$$

Training events may only be held at a subset of the set of input candidate ranges. That subset of ranges may be no bigger than MAX_RANGES , and no smaller than MIN_RANGES .

Constraints C11 and C12 make use of indicator variable $y_2[r]$ to accomplish this, since range r may only hold events when $y_2[r]$ is equal to 1. Constraint C11 forces $y_2[r]$ to equal 0 for all but MAX_RANGES ranges. Constraint C12 forces $y_2[r]$ to equal 1 for at least MIN_RANGES ranges:

$$C11. \quad MAX_RANGES \geq \sum_R y_2[r]$$

$$C12. \quad MIN_RANGES \leq \sum_R y_2[r]$$

No more than MAX_RANGE_EVENTS can be held at any individual range. For any range r , $y_1[e, r]$ may equal 1 for events e up to MAX_RANGE_EVENTS , and no other events e may be held at range r . Also, indicator variable $y_2[r]$ must equal 1 when one or more events are assigned to range r , since the sum of events $\sum_E y_1[e, r]$ must equal 0 whenever $y_2[r]$ equals 0.

$$C13. \quad MAX_RANGE_EVENTS * y_2[r] \geq \sum_E y_1[e, r] \quad \text{for each } r \in R$$

At least MIN_RANGE_EVENTS must be held at an individual range for that range to hold any events during the year. For any range r , $\sum_E y_1[e, r]$ must be greater than or equal to MIN_RANGE_EVENTS , or else equal 0.

$$C14. \quad MIN_RANGE_EVENTS * y_2[r] \leq \sum_E y_1[e, r] \quad \text{for each } r \in R$$

4. Potential Applications

The presented modeling framework provides a starting point for asking and beginning to address several questions of potential interest to USAF. This chapter provides a sampling of such questions and guidance on how the framework might be used to address them.

Understanding the Value of Strategic Basing

- **What is the difference in costs between the planned basing strategy and the optimal basing strategy?**

The Air Force has a planned way forward for basing the F-35A fleet. Flying hour costs associated with exercise participation for “optimal” beddown strategies can be compared with those for the planned basing strategy to gain insight into the *value* of strategic basing.

- **What fraction of total flying hour program costs are associated with participation in exercises?**

The presented modeling framework estimates costs associated with participation in regional training exercises, which is just one component of training requirements for CMR pilots. Knowing the fraction of the total flying hour budget composed of costs associated with exercise attendance can illuminate the relative importance of considering training requirements in future basing decisions.

- **What alternative basing strategies satisfy a range of minimum cost solutions?**

Factors other than costs alone may inform basing decisions. The presented framework can be used to identify not just the optimal solution for cost but also a set of perhaps slightly less optimal solutions that account for feasibility of implementation. For instance, if a particular base or training range is an untenable option for political or other reasons, the base or training range can simply be removed from the potential solution space when the model is run.

Implications for Range Modernization

- **What is the tradeoff between flying hour costs and costs of range modernization?**

The optimization model described in this report is not equipped to provide a full cost-benefit assessment of candidates for range modernization. Such an assessment would require additional analysis of the actual costs associated with completing upgrades, which

is uncertain and might not be uniform across the enterprise. However, adjusting the model's parameters to vary candidate training locations and limits on exercise frequency and size can provide a baseline of flying hour costs against which to compare the costs of upgrading different sets of USAF ranges.

- **Is there a “sweet spot” in terms of the number of ranges on which to focus modernization dollars?**

One output of the model would be the choice of training locations that yield the least flying hour costs for meeting requirements for regional training. Observing how the optimal basing strategy varies as a function of fleet mix, training requirements, and other parameters can provide a sense of the size and characteristics of the set of training locations that reduce enterprise flying hour costs. It is possible that slight increases in flying hour costs associated with using a small number of ranges would be offset by the reduced cost of range modernization and maintenance. Thus, it might make sense to modernize only the minimum number of ranges. The presented modeling framework facilitates the types of analysis needed to test this hypothesis.

Implications for Composite Force–Training

- **What is the contribution of other platforms that support F-35 training to total flying hour costs?**

It is clear that the F-35A will train with aircraft of different types. By including the option to assess flying hour costs *across* all relevant types of aircraft, the framework is positioned to provide insight into the contribution to enterprise-wide costs of aircraft that might support F-35A training. The proportion of training exercise costs incurred by other platforms could be significant and therefore influential in determining training locations as well as F-35A base locations. On the other hand, it is possible that the locations of other platforms have little or no effect on total costs, either because these platforms participate without traveling to training events, or because the traveling platforms are few in number or are geographically situated such that they can attend events at chosen ranges without having to travel extreme distances. In this case, an optimal basing strategy for the F-35A would look very similar to an optimal enterprisewide basing strategy.¹⁴

¹⁴ It is possible that some of these other platforms might participate in these events within existing flying hour programs to achieve their own RAP events and therefore might not contribute to costs of the decision process.

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Since 2009, the U.S. Air Force has been working toward increasing the strategic nature of domestic basing decisions through the formalized Strategic Basing Process. This report presents a modeling framework designed to identify basing locations for the F-35A fleet and training range locations that minimize enterprisewide flying costs associated with participation in required composite force training exercises for combat mission-ready pilots.



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